2020-2021

The SSGF/LRGF Magazine

STEWARDSHIP SCIENCE

BLASTS PAST

Livermore's unusual film-preservation project

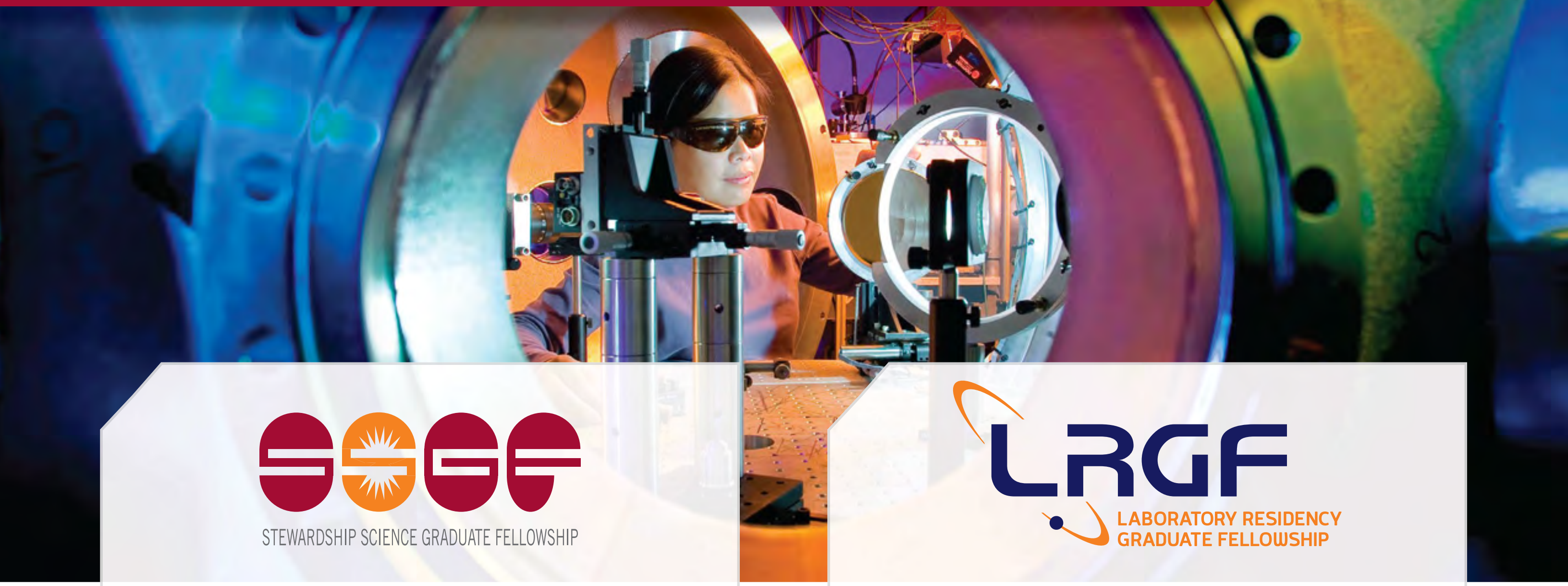
Sandia: A whole lot of shaking underground

Los Alamos: Old plutonium, new technology

Plus: Fellows on location, microchips retooled, Thor's dynamic hammer, atmospheric-disturbance surveillance and more

ANNOUNCING THE 2020-21 INCOMING FELLOWS

DEPARTMENT OF ENERGY NATIONAL NUCLEAR SECURITY ADMINISTRATION



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STEWARDSHIP SCIENCE

SSGF LRGF

Stewardship Science: The SSGF/LRGF Magazine showcases researchers and graduate students at U.S. Department of Energy National Nuclear Security Administration (DOE NNSA) national laboratories. *Stewardship Science* is published annually by the Krell Institute for the NNSA Office of Defense Program's Stewardship Science Graduate Fellowship (SSGF) and its Laboratory Residency Graduate Fellowship (LRGF), both of which Krell manages for NNSA under cooperative agreement DE-NA0002135. Krell is a nonprofit organization serving the science, technology and education communities.

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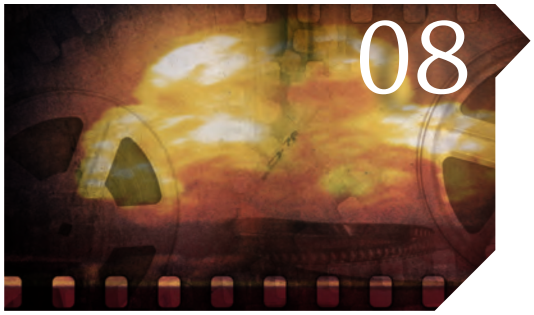
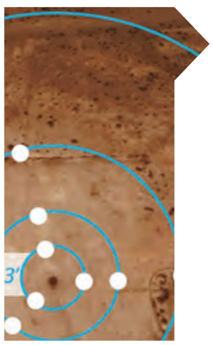
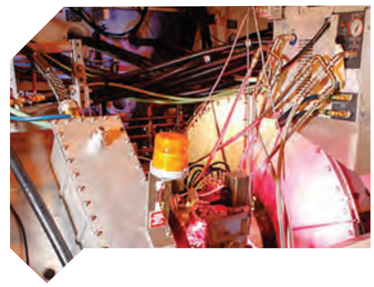
FEATURES







DEPARTMENTS

ON THE COVER

A deteriorating film canister containing footage from the Manhattan Project's Trinity detonation. For more, see "Bombs on Film," page 8.

The Department of Energy National Nuclear Security Administration Stewardship Science Graduate Fellowship (SSGF) and Laboratory Residency Graduate Fellowship (LRGF) outgoing classes describe their lab experiences.

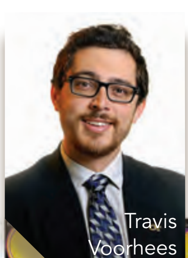
COMPRESSIVE FORCE

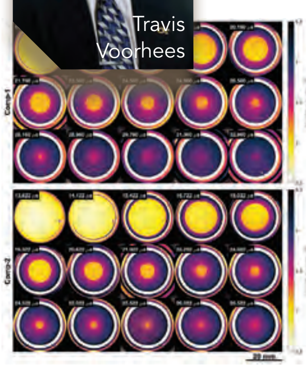
LRGF recipient **Travis Voorhees** competed in decathlons and pole vaulting at California State Polytechnic University in Pomona until an injury forced him to stop. He turned to research, working to extend biomedical joint implants past their standard 20-year lifespan.

Now working with Ph.D. advisor Naresh Thadhani at the **Georgia Institute of Technology**, Voorhees studies how brittle, granular materials, such as soils and concrete, behave when subjected to intense shock compression. To construct a tool that predicts materials' transition from grains to a dense solid, or compaction, Voorhees simulates the mass crushing of individual grains into a big block. Calibrating such models requires experimental data. Many existing compaction simulations rely on data from one-dimensional experiments but are applied to three-dimensional scenarios.

To see what happens to grains during extreme shocks, Voorhees combines experimental and computational research using a model powder. The work is part of an ongoing collaboration with Los Alamos National Laboratory.

At Georgia Tech, Voorhees has used gas guns to conduct shock compaction experiments that have reduced experimental uncertainty to 1 percent or less from 5 to 50 percent. During his LRGF work at Los Alamos, he improved computational models by including factors that others have ignored. Voorhees' test material is strong and brittle; its durability should create some resistance to shear loading, internal forces that can cause the materials to deform. "We've begun investigating how to couple compaction and strength models for granular materials," he says. "Then we'll be able to incorporate shear loading." He hopes to apply such models to more realistic scenarios, such as mining explosions or a meteorite impact on Earth.





Travis Voorhees – the first LRGF recipient to complete the program – produced this composite radiograph from two compaction experiments at Los Alamos National Laboratory's PHELIX facility. He's been modeling soil, concrete and other brittle, granular materials under intense shock compression. Pictured here: cerium dioxide; the colors reflect variations in material densities.

NOVA DETECTIVE

Growing up near the Three Mile Island plant in Pennsylvania, SSGF recipient **Erin Good** always was aware of nuclear energy and grew ever more interested in the science behind it. For her graduate research, she pursued nuclear astrophysics, particularly the processes in novae – stellar explosions that occur as a white dwarf star accretes matter from a nearby companion star and becomes hotter and denser. The explosions produce detectible light bursts that take thousands to millions of years to reach Earth observers, who analyze them for clues to the elements cooked in these stellar furnaces.

Erin Good designed and built this silicon detector array now installed at Florida State University.

On Earth, nuclear astrophysicists model stellar fission with computer codes, but simulations require experimental data. When Good entered Catherine Deibel's **Louisiana State University** group in 2014, she joined the effort to move a massive Enge split-pole spectrograph from Yale University to Florida State University's John D. Fox Superconducting Linear Accelerator Laboratory. Good refurbished the instrument's focal-plane detector and designed and built a silicon detector array, tools that she's used since then in experiments. Last fall she measured the decay of calcium isotopes via proton emission. The ratio of protons detected over the total number of times an isotopic state is populated, or branching ratio, allows her to determine how quickly decay is happening and whether it occurs solely from protons or involves other mechanisms such as gamma rays.

During her 2017 Lawrence Livermore National Laboratory (LLNL) practicum, Good analyzed data from beta- and gamma-ray spectroscopy experiments of yttrium-96, rubidium-92 and other isotopes to pinpoint their beta decay. These processes are implicated in the antineutrino anomaly, a difference between the measured and expected flux of these particles. Scientists are still trying to explain whether this discrepancy points to measurement problems or a novel type of antineutrino. She continues to work on the problem with LLNL colleagues and LSU professor Scott Marley.

EXTREME WATER

Viktor Rozsa has studied materials under extreme pressure and run chemistry simulations for a long time, first as a physics major at Hillsdale College and now as a **University of Chicago** graduate student with Giulia Galli.

While an undergraduate, Rozsa spent a summer at the Carnegie Institution for Science in Washington, studying hydrogen stored in cage-like molecules, which requires applying extreme pressures.

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Tough Chips

Bunny-suited workers inside the yellow-glowing rooms of a New Mexico plant make integrated circuits that are crucial for the nation's nuclear stockpile security, working with tools as bulky as a small train car, says Mike Holmes, the facility's senior manager.

He's describing the ion implanter at Sandia National Laboratories' sprawling Microsystems Engineering, Science and Applications (MESA) complex outside Albuquerque, a Department of Defense-accredited microelectronics production facility and research and development powerhouse. The implanter injects various kinds of charged atoms to change, in complex ways, the electronic properties of pure silicon wafers.

That is early in "a process that takes many hundreds of steps to build a product," Holmes says. Before emerging, MESA's evolving microchips may have also been exposed to light, bathed in acids, sliced and diced, and trimmed at various stages with a polishing wheel.

MESA specializes in producing radiation-hardened microchips, Holmes says – modifying circuits' architectures to make them immune to radiation or "changing the recipe we use to fabricate the microelectronics."

Meanwhile, MESA's highly skilled fabricators build intricate hardware for visiting scientists and engineers who also depend on the facility for early-stage investigations. "We work extensively with academia, other government agencies and other national laboratories on research collaborations," Holmes says.

One key to that mission is MESA's two separate chip fabrication facilities, one that makes bread-and-butter silicon microelectronics and another for R&D that makes compound semiconductors, complex structures produced with other semiconducting elements. Non-silicon building materials are typically members of the periodic table's III and V groups. Examples are gallium arsenide, indium phosphide and aluminum nitride.

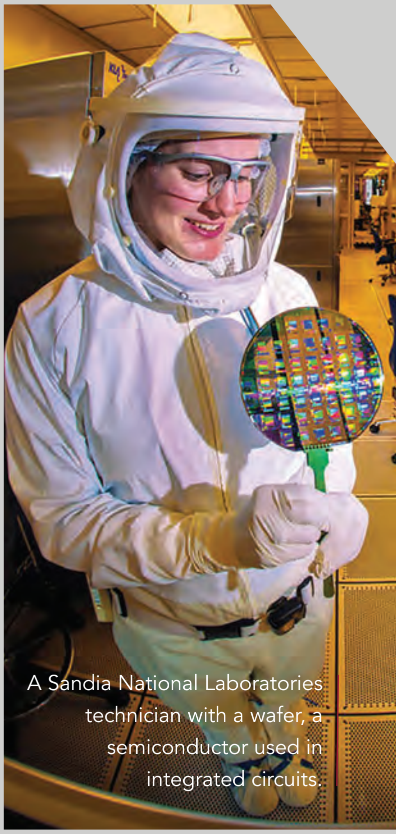
This two-fab flexibility exposes Sandia chipmakers and the researchers they work with to ranges of advanced technologies such as high-speed photonics, microelectromechanical systems (MEMS) and ultrawide-bandgap electronics.

MEMS marry data-processing integrated circuits with other microdevices that can respond to their surroundings – for example, directing fluid flow within inkjet printers. Ultrawide bandgaps are energy barriers that can be breached to let electrons of certain semiconducting atoms convey electricity at unusually high voltages, frequencies and temperatures.

MESA research collaborations have led to a number of awards for innovation from *R&D World* magazine.

One example, billed as the world's fastest multiframe digital X-ray camera, can register images almost every billionth of a second, 25 times faster than any digital camera. It also resists ionizing radiation. Such quick exposure times and hardiness could let it document plasma movements in controlled but violent nuclear fusion experiments, researchers say. MESA made it by sandwiching and bonding radiation-hardened silicon microchips and light-sensing photodiodes.

Another advance, ultrawide-bandgap power electronics, could replace transformers with smaller transistor-based technology that is faster-switching, more efficient and cheaper. Built with compound semiconductors, it can also operate at higher temperatures and tolerate radiation, making it attractive for use in future energy grids and defense applications.


A Sandia National Laboratories technician with a wafer, a semiconductor used in integrated circuits.

A third innovation, the gas analyzer on a chip, is a solid-state sensor that can measure all Environmental Protection Agency-regulated emissions and thus monitor exhausts from engines, turbines and power plants. It can operate in high temperatures without cooling and is mass-producible at low cost.

Such research activities continue even while MESA works through an almost three-year production pause to retool from fabricating 6-inch silicon wafers to 8-inch versions.

The switch is "really driven by sustainment of our supply chain for wafers and support for our tools," Holmes says. Outside industries that supply both are scaling up.

"The newer tools to handle 8-inch wafers are much larger and heavier," he adds. "So some of the challenges are just installing them."

A striking example is the ion implanter in MESA's silicon microelectronics production line, which weighs more than 36,000 pounds. Notes Holmes, "It took us six months to clean up and remove the old one and install the new one."

Monte Basgall

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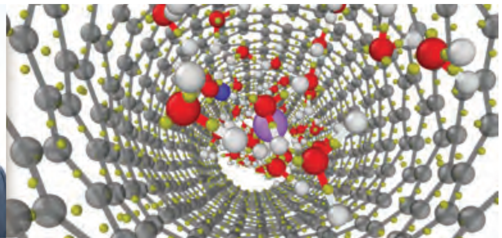


During his Livermore practicum, Viktor Rozsa simulated water confined in carbon nanotubes.

He used X-ray diagnostics at Argonne National Laboratory's Advanced Photon Source to unravel the system's exotic behavior. "I think of the high pressure dial as a unique and effective way to understand the full possibility of a material and its technological applications," he says.

Rozsa has continued studying materials under extremes, now with computation. In a 2018 *Proceedings of the National Academy of Sciences* paper, he and colleagues simulated water at pressures up to 20 gigapascals and at hundreds of degrees Celsius, conditions that occur deep in the Earth or on other planets. They've shown that it can act as a complex fluid, forming many short-lived ions that make it more electrically conductive. Now they're modeling water mixed with ions such as lithium, sodium and potassium under these extreme conditions, more like what might exist in realistic planetary environments.

For his 2017 LLNL SSGF practicum, Rozsa studied pure water and ionic solutions in small, confined spaces such as carbon nanotubes. A recent *Journal of Chemical Physics* paper described how such spaces change water's structure. Disruptions to the liquid's hydrogen bonding network and surface effects in the nanotube imprint unique changes on water molecules' quantum properties, such as their charge distribution.

RIDING GRAVITATIONAL WAVES ▶

A. Miguel Holgado had just started graduate school in February 2016 when researchers reported that they had detected gravitational waves from two black holes merging, a century after Albert Einstein first predicted that such waves existed. Holgado soon pivoted to that topic for his astrophysics research at the **University of Illinois at Urbana-Champaign**.

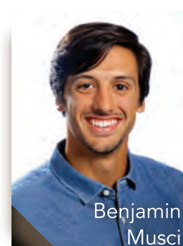
Since then, Holgado has used computational models to explore the sources of gravitational waves: How did black hole binaries and neutron star binaries form? And where do they come from? (Binaries are two celestial bodies in close orbit.)

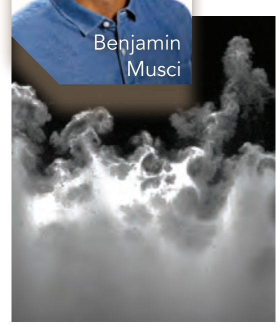
Interactions between black holes and neutron stars produce the detected gravitational waves, but both of these cosmic objects are made from massive stars, which are vanishingly rare. Holgado has developed models to examine these interactions and has predicted that the progenitors of binary black holes and neutron stars also could produce gravitational waves.

Holgado wants to compute a range of gravitational wave signatures that could be of interest for future such experiments "to see more than binary inspirals, also other things like supernova kicks," he says, velocity bursts from these asymmetric explosions that can eject neutron stars or black holes. Those experimental observations will require different types of gravitational wave detectors. The ground-based Laser Interferometer Gravitational-Wave Observatory (LIGO) detects only a sliver of the spectrum, a frequency range of tens to thousands of hertz. An orbiting instrument, the Laser Interferometer Space Antenna (LISA), scheduled to launch within the next 20 years, will detect gravitational waves in the millihertz (thousandths of a hertz) range. Ultimately, gravitational wave astronomy could, like electromagnetic astronomy, have a range of instruments available to capture signatures across the spectrum, Holgado says.

During his 2017 SSGF practicum at LLNL, Holgado helped design laser experiments to produce electron-positron plasmas in the laboratory. Such plasmas can occur in astrophysical environments, such as the jets that form during binary neutron star collisions.

EXTREME MIXING ▶





An example of the fluid mixing Benjamin Musci studies. It's an important process in inertial confinement fusion experiments and supernovae physics.

Inspired in part by an uncle who worked at NASA's Johnson Space Center, **Benjamin Musci** studied mechanical engineering so he could work on significant problems, particularly climate change. While an undergraduate at Ohio State University, he studied experimental fluid dynamics and designed a model strategy for eliminating intermittent drag on high-speed aircraft.

When the SSGF recipient started graduate school at the **Georgia Institute of Technology**, he wanted to combine fluid dynamics with clean-energy applications. Working with Devesh Ranjan, he's built an experimental facility to test extreme fluid dynamics events that can occur in inertial confinement fusion (ICF) experiments, where high-energy lasers implode a small fuel capsule. Shell defects can cause the materials to mix, perturbing and degrading the fusion reaction in unpredictable ways. Musci runs model experiments of these events, applying high-energy shockwaves to gases of different densities, such as nitrogen and carbon dioxide, combining them in complex patterns like creamer in coffee. He and his colleagues can observe the entire mixing process, rather than

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Eyes in the Skies

A researcher prepares a part from a Global Burst Detector for testing in Sandia National Laboratories' Flight Test Chamber. Sandia collaborates with Los Alamos National Laboratory on science and technology behind the satellite system that detects nuclear detonations.

The Global Positioning System (GPS) guides pilots through cloudy skies and steers vacationers to attractions. Geostationary (GEO) satellites help deliver weather forecasts and internet, TV and radio. Both sets of orbiters also serve a less-obvious critical purpose: national security.

The satellites carry sensors to detect aboveground nuclear explosions that, via ground-based systems, immediately inform the nation's leaders of any such detonation, anywhere in the world. It's called the United States Nuclear Detonation Detection System (USNDS).

The GPS-borne Global Burst Detectors (GBDs) and the GEO-borne Space and Atmospheric Burst Reporting Systems (SABRS) are developed and launched through a collaboration of the Department of Energy National Nuclear Security Administration (DOE NNSA), the Department of Defense (DoD) and other government agencies. In space's harsh environment, the satellites and payloads have a 10-year lifespan, which creates an ongoing demand for new sensing payloads. One recent deployment was in August 2019, when the U.S. Air Force launched the second in a new satellite series dubbed GPS Block III from Cape Canaveral Air Force Station in Florida.

Under the DOE NNSA, roughly 300 engineers, scientists and other professionals at Los Alamos and Sandia national laboratories collaborate to design, build and support on-orbit fielding of GBD and SABRS payloads.

The project dates to the early 1960s when the Limited Test Ban Treaty went into effect, allowing participating nations to verify others' adherence. The first sensing payloads were launched in 1963 and the system transitioned to GEO and GPS satellites in the 1970s and 1980s.

The science of detecting nuclear detonations that might occur anywhere from Earth's surface to high altitudes to near-Earth space continues to improve. Researchers are replacing obsolete parts while reducing sensing-payloads' size, weight and power use to fit into new satellite designs.

The USNDS sensor payloads can detect the signs of a nuclear detonation. Los Alamos develops devices that can catch the types of neutrons, gamma rays, X-rays, charged particles and electromagnetic pulses that result from nuclear bursts. Sandia designs and builds optical sensors that can capture the explosions' light signature.

The teams subject the components to a gauntlet of tests. No single challenge to a sensor's survival is greater than another: rocket vibrations during launch, the shock of explosive bolts releasing the satellite into orbit, extreme temperature changes as it passes in and out of Earth's shadow, and radiation exposure. All of those events threaten hardware in space.

Ensuring the performance of USNDS sensor payloads before launch requires unique facilities at the labs, including thermal vacuum chambers, gamma, X-ray and neutron irradiators, charged-particle accelerators, vibration- and shock-testing facilities, and anechoic chambers, which block outside electromagnetic radiation during tests to detect unwanted crosstalk between devices. Each test's rigor depends on the launch vehicle, the intended orbit and the host satellite's constraints.

Once a payload has passed all tests, the lab teams work with DoD, other government agencies and their contractors to integrate the payload into a satellite. There's also lengthy testing to ensure performance over a long life.

Andy Boyles

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just the period immediately after implosion or in the throes of the fusion reaction.

Similar extreme mixing occurs in supernovae. Stars have dense elements such as iron in their cores with the light elements helium and hydrogen at their outermost layers. Current astrophysical hydrodynamics simulations don't accurately capture how those elements mix. Heavy elements from the core reach the star's exterior much sooner than models predict, Musci says.

Musci focused exclusively on climate models for his 2017 LLNL practicum. He examined a 20-year period, analyzing whether their predictive capabilities had improved. The project required him to work with Linux and learn Python. He completed a second Livermore practicum remotely in summer 2020 to build a computational model of his extreme fluid-mixing experiments.

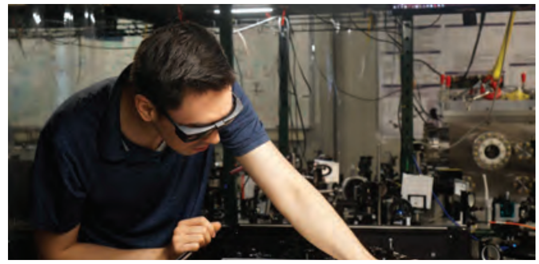
LASER FOCUSED

Daniel Woodbury has explored interesting interactions between high-intensity mid-infrared lasers and matter with Howard Milchberg at the **University of Maryland, College Park**. At first, he examined laser wakefield acceleration in high-density gas jets, a strategy that could lead to portable particle accelerators. As laser pulses interact with the gas, the intense field locally expels electrons. At the pulse's end, electrons are pulled back to their original locations – like a boat's wake – producing large plasma waves and a strong electric field. Outside plasmas, such extreme electric fields are destructive – the reason that high-energy accelerators require kilometer-sized structures. But by using stronger fields in plasmas, researchers hope to scale such experiments down to a more manageable size.

Daniel Woodbury

Woodbury and his colleagues also developed a laser-based strategy to detect radioactive material from up to 100 meters away. Radiation knocks electrons off nearby atoms and molecules in air. A laser beam can heat these free electrons, spurring electron avalanche, a runaway cascade of ionization that produces a spark. To detect radioactivity, the team pulsed a sample with ultrashort bursts from a mid-infrared laser (3.9 micron light wavelength), which maximized the electron avalanche effect and minimized other competing ionization mechanisms.

Detecting radioactivity sparked a new insight: "Not only were we sensitive to single electrons, but also we could see exactly where they had been," Woodbury says. With such brief pulses – 70 trillionths of a second – the micron-sized spark they observed didn't have time to move far from the original electron. So Woodbury devised experiments to study laser ionization in air and other gases over a huge dynamic range. He and his colleagues have also explored using lasers to generate terahertz radiation, a difficult-to-achieve frequency



Daniel Woodbury fine-tunes his laser setup.

band between microwaves and infrared that shows promise in a range of applications from medical imaging to national defense.

During his 2018 SSGF practicum with Sandia National Laboratories' MagLIF group, Woodbury diagnosed plasma conditions with Thomson scattering. These results can help researchers learn more about plasma temperature and density and the energy absorbed.

HUNTING NEW MATERIALS

Sergio Pineda Flores

Sergio Pineda Flores chose computational chemistry for its usefulness in a range of fields, including physics, materials science and biochemistry. "I'm a jack of all trades at this point," says the SSGF recipient.

Science teachers at his Washington, D.C., high school seeded his broad interests. Even his cross-country running coach worked at the U.S. Naval Research Laboratory. Later, as a chemistry major at Haverford College, Pineda Flores got his first taste of computational chemistry research with Joshua Schrier, using density functional theory to discover new materials.

In his graduate studies with Eric Neuscamman at the **University of California, Berkeley**, Pineda Flores has focused on quantum Monte Carlo (QMC) methods, techniques that can improve the accuracy of molecular energy calculations while limiting computational demands. He implemented orbital optimization for QMC, a feature that lets researchers refine estimates of the probable space that electrons in excited states can occupy. These improved calculations can help scientists better understand optical band gaps as they search for materials that can harness solar energy, among other applications.

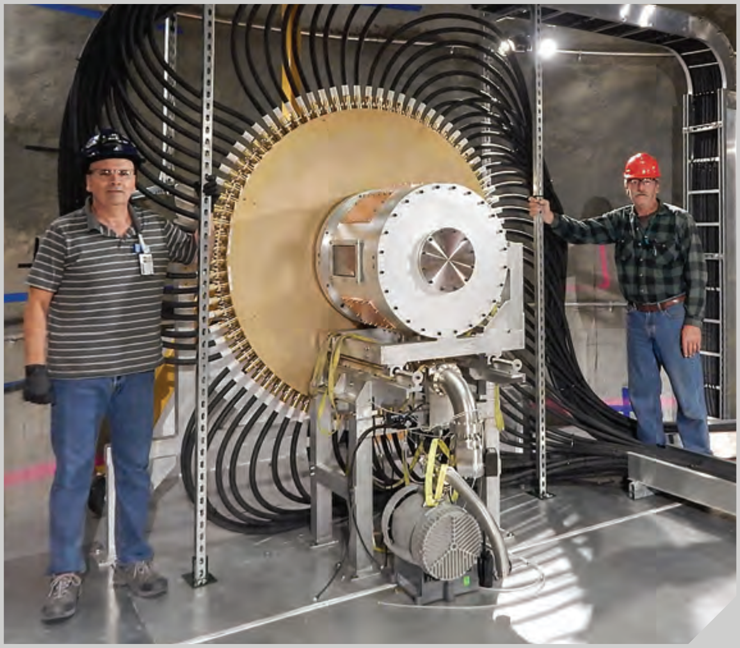
Pineda Flores has tested these techniques with manganese oxide and iron oxide, a catalyst to split water and produce hydrogen fuel, the latter during his 2019 practicum at Sandia National Laboratories in New Mexico. At Sandia Pineda Flores also worked on molecular dynamics simulations of lithium fluoride, a potential window material for shock experiments, calculating the dielectric constant of that substance at a wide range of temperatures and pressures.

In late August, Pineda Flores began work as a computational scientist at Lawrence Livermore National Laboratory.

Neutron Hammer

Building 391 at Lawrence Livermore National Laboratory feels like an aircraft hangar: lots of space overhead. It's locally famous as the site of the first X-ray laser demonstration. This day a small group has come to see a device found down a passage through the floor: a dense-plasma-generating, neutron-producing machine called MJOLNIR, after Thor's hammer.

The visitors, led by Livermore research scientists Yuri Podpaly and Alexander Povilus, descend metal stairs to face MJOLNIR. The first four letters are pulled from megajoule; the last three from neutron imaging radiography. Giant cables snake from a shiny transmission plate that conducts the plasma-inducing current. Nearby is a camera with a nanoseconds-long shutter speed.



MJOLNIR team members with the device's cable-festooned transmission plate, which creates the strong electrical fields necessary for neutron radiography.

Radiography is an important tool in stockpile stewardship science, a discipline that has evolved over the past three decades to assess aging weapons under limitations of a nuclear test moratorium. The national security labs have found flash neutron radiography a valuable tool for producing high-contrast snapshots inside static objects that are opaque to X-rays. MJOLNIR, though, is unlike other previous neutron radiography devices: It's a prototype for capturing dynamic experiments – for imaging ultrafast-moving materials, such as metals propelled by high explosives.

The cables run another level below, to a suite of towering generators – Marx bank driver modules that, like those at Sandia National Laboratories' Z machine, produce a high-voltage pulse from a low-voltage current.

The neutrons are spawned from a high-energy ion beam that forms during the final stage of the plasma discharge, when high voltage is applied across low-pressure deuterium or tritium gas between cylindrical electrodes. The brawny charge ionizes the gas and lets a high current – millions of amperes – flow through the plasma, creating a powerful magnetic field. The magnetic force squeezes the plasma into a small high-density region, or pinch, at a central electrode's artillery-shell-like tip. This generates electric fields that can accelerate the ions to several mega-electron volts. When beamed at a target – in this case the dense plasma that forms at the beam's front – the ions produce penetrating neutrons.

MJOLNIR is surrounded by an extensive array of diagnostics – light diodes, spectrometers, a neutron time-of-flight detector – that will yield plasma and neutron data invaluable for refining the device for subsequent experiments. The data from these diagnostics will help researchers hone high-performance computing models, an advantage MJOLNIR has over previous machines – known as dense plasma focus devices, or DPFs – that relied on trial-and-error for fine-tuning.

"To guide our ability to design these things," Povilus explains, "we feed the information to our simulation crew. They do the validation that will give us our next design. It's nice to get the physics spot on."

Researchers will continue to put the device through stringent flash-radiography trials and development under Building 391's floor. If it passes those tests, they'll deploy MJOLNIR at Site 300, an explosives test facility 15 miles from Livermore.

Bill Cannon

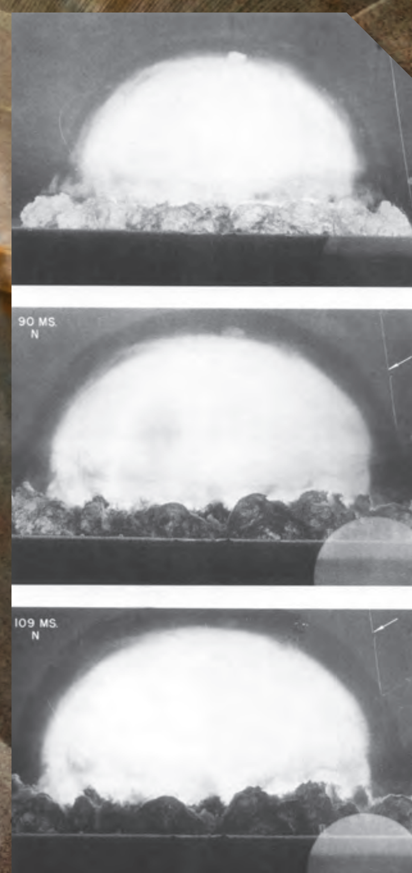
COVER STORY

BOMBS ON

BY MIKE MAY

FILM

NO, NOT *CATS* AND *ISHTAR*. A LIVERMORE CREW PRESERVES FILMS OF NUCLEAR TESTS THAT, ON FURTHER ANALYSIS, REVEAL UNEXPECTED FINDINGS.



Frames from the Trinity atomic bomb test, the first.

In August 2011, weapon physicist Greg Spriggs started an immense, complicated and unexpectedly intriguing project: archiving films of U.S. nuclear tests. Scientists tracking the 210 atmospheric experiments – from Trinity in 1945 to the last blast in 1962 – generated thousands of films, and time was running out to save them. As Spriggs would discover, these old movies held explosive secrets.

Spriggs started the project alone at Lawrence Livermore National Laboratory, hoping to create archival copies of the footage. For some films, the rescue came too late. But beyond a reel's condition, Spriggs struggled with the archival process. "I had many false starts scanning it," he says. "I'm not an expert in handling films." That created a big problem when facing thousands of them.

Spriggs thinks that as many as 9,000 nuclear test movies exist. So far, he's obtained about 6,000 and at least another 2,000 or so could be in an archive at the Defense Threat Reduction Information Analysis Center (DTRIAC) in Albuquerque, New Mexico. Spriggs recruited film expert Jim Moye to scan all that footage.

To select equipment for capturing the tests, the Department of Defense (DoD) turned to EG&G, once known as Edgerton, Germeshausen, and Grier Inc. Among this trio, Massachusetts Institute of Technology electrical engineering professor Harold Edgerton stood out as a pioneer in the field of high-speed imaging, and the 1940 film, *Quicker'n a Wink*, on stroboscopic photography, even won an Oscar. Although many people know of Edgerton's images that froze bullets in flight and milk drops in mid-splash, few are aware of EG&G's secret government contract to film nuclear tests.

The company did more than just make many, many images of tests. EG&G used a variety of technologies but captured most of the events in black and white, using color only for about 10 percent of the films. "After 45 years in the film industry, I've seen lots of formats," Moye says, "but among the formats used to capture the detonations, there are a few I'd never seen."

The nuclear test films ranged from 8mm, a familiar size for old-school home movie buffs, to 9.5 inches, including a 70mm format that was new to Moye. Even within a certain film gauge, Moye faced different formats, such as the number of perforations – or lack of any perforations. Plus, the documenters used glass plates – 4-by-5 or 4-by-6 inches – for some still images. "Glass plates have been a format for stills since the mid-1800s," Moye explains, "and the emulsion on glass is really stable dimensionally." That is, the glass plates don't shrink the way standard celluloid film does over time.

Far left: A moment captured during the Turk test, March 7, 1955 – one of more than 7 million scanned frames from film of above-ground nuclear detonations. Rockets fired before the blast formed a grid in the sky, providing reference points for analyzing the blast's size. *Middle:* Turk's fireball, which can be used to analyze the shock wave. *Near left:* Harlem, from June 12, 1962, capturing a light pulse; time between light pulses in a nuclear explosion relates to yield.

There are multiple kinds of movies because the nuclear testers needed to document a range of phenomena. For the early mushroom-cloud formation, the crews captured images at 24 to 100 frames per second. Filming the cloud's entire rise could take up to 40 minutes. Other features required much faster cinematography.

Although 35mm is a common film format, it wasn't available in rolls that could run at high speed. To document a nuclear detonation fireball, cameras exposed 2,000 to 3,000 frames per second. For that, crews used 16mm or 8mm film that came in 100-foot rolls equaling 4,000 or 8,000 frames, respectively. That enabled high speed but produced small images, which meant low spatial resolution.

So, around the late 1950s, EG&G asked Photo-Sonics – a company that specialized in photographic instrumentation, and still does – to develop cameras that could run 35mm and 70mm film at high speeds. In 1962, EG&G first used some of these new machines to record the test series code-named Dominic.

Preserving these historic movies isn't as simple as putting film on a scanner and grabbing images. Even getting at the footage can be challenging. "A few of the Trinity rolls took some pounding to get the cans open," Moye says. "They must have been exposed to some moisture, because they were rusted."

Plus, Spriggs and Moye needed to determine film shrinkage. "EG&G allowed for that," Moye says, "by exposing a grid or measurement tool at the head and tail of rolls, but, unfortunately, lots were cut off." So he's measured the size of about 300 movies by hand. "Most of the films today are 60 to 70 years old, and they've shrunken 1 to 1.5 percent."

The team started by scanning some 70mm films. Moye placed the film, frame by frame, on a flat-bed scanner, registering it by eye. He still scans the 5.5- and 9.5-inch movies that way.

Luckily, the team acquired a Golden Eye II scanner from Sweden-based Digital Vision, letting Moye load and automatically image formats ranging from 8mm to 70mm. Plus, the device doesn't use perforations to advance the frames, allowing Golden Eye II to work with the range of formats. Not least, Moye notes, "it registers the film digitally, so it doesn't care if it's shrunken."

So far, the scanned collection covers about 4,500 films of above-ground tests. Altogether, they comprise about 7.3 million scanned frames, including some from the Turk test on March 7, 1955, which shows smoke from rockets fired before the blast to provide a grid of sorts that could be used later for reference in analyzing the blast's size.

In addition to atmospheric tests, the scanned collection also includes recordings of some underground explosions. Overall, the current archive consists of about 5,000 films, many of them now unclassified. Spriggs explains that "the Atomic Energy Act in 1947 decided that anything after detonation could be unclassified, and the information could be released if the government felt it could not help someone develop a nuclear weapon." Spriggs is what's known as a derivative declassifier; to ensure there's no classified information on a film, a second derivative declassifier watches the film with Spriggs, and they both must sign off after reviewing it. The reviewers file paperwork with the Department of Energy (DOE) office of classification for approval. Most of the scanned films – all but about 700 – are now public.

All that recorded information takes up huge amounts of computer storage. The project started with about a 15-terabyte server in 2011, then moved up – to 40 terabytes, then 140 and now 300. Plus, it's all backed up in two other places.

Preserving the archival value of these films is just part of the process. They hold crucial information about the power of the blasts, but getting it takes some detective work. Moye says "the fun but challenging part is learning something about what EG&G was doing – how they photographed the tests and what's important. By understanding what we need to get from the films, I can look out for problems, like making sure that we get everything, such as timing marks." Also, he watches for different things when scanning the various formats, which were used to capture specific test features.

For EG&G, analyzing the films proved challenging. Using a Kodagraph – a big photographic enlarger made by Eastman Kodak – the company team could magnify a frame by about 20 times. EG&G would shine the image on a grid and have three people make independent measurements of the size of a test's fireball on each frame. Technicians then took the average of the three figures.

"Even magnified by 20 times, the fireball is only an inch or inch and a half across," Spriggs says. The fireball size over time can be used to calculate a test's explosive yield.

With a scan, Spriggs can examine a detonation more closely. "We can make the fireball 10 or 15 inches on the screen," he says, "and we have tools that look at the optical density of the film – the edge of the shockwave," such as in the fireball of the Turk test. "Plus, we have a more accurate algorithm."

With better measurements and an improved algorithm, Spriggs finds values that routinely vary from the original EG&G results by as much as 5 percent to 20 percent.

In thinking back on this work, Spriggs says that reconstructing what EG&G did created the biggest challenge. "We don't have all the paperwork, and the people are long gone. So we put together all of the bits and pieces."

That has meant spending lots of time going through the company's data and comparing results. "We expected small changes but, as you see, we found some big changes."

Even when EG&G used new cameras for the Dominic test, problems arose. The technicians placed three different devices on nearby Christmas Island to locate the blast with triangulation. A plane dropped the bomb with a parachute, giving its crew time to escape before the blast. The wind moved the parachute, but something went wrong in locating the explosion, affecting the yield estimates. From the three films, EG&G calculated different results – off by a factor of two.

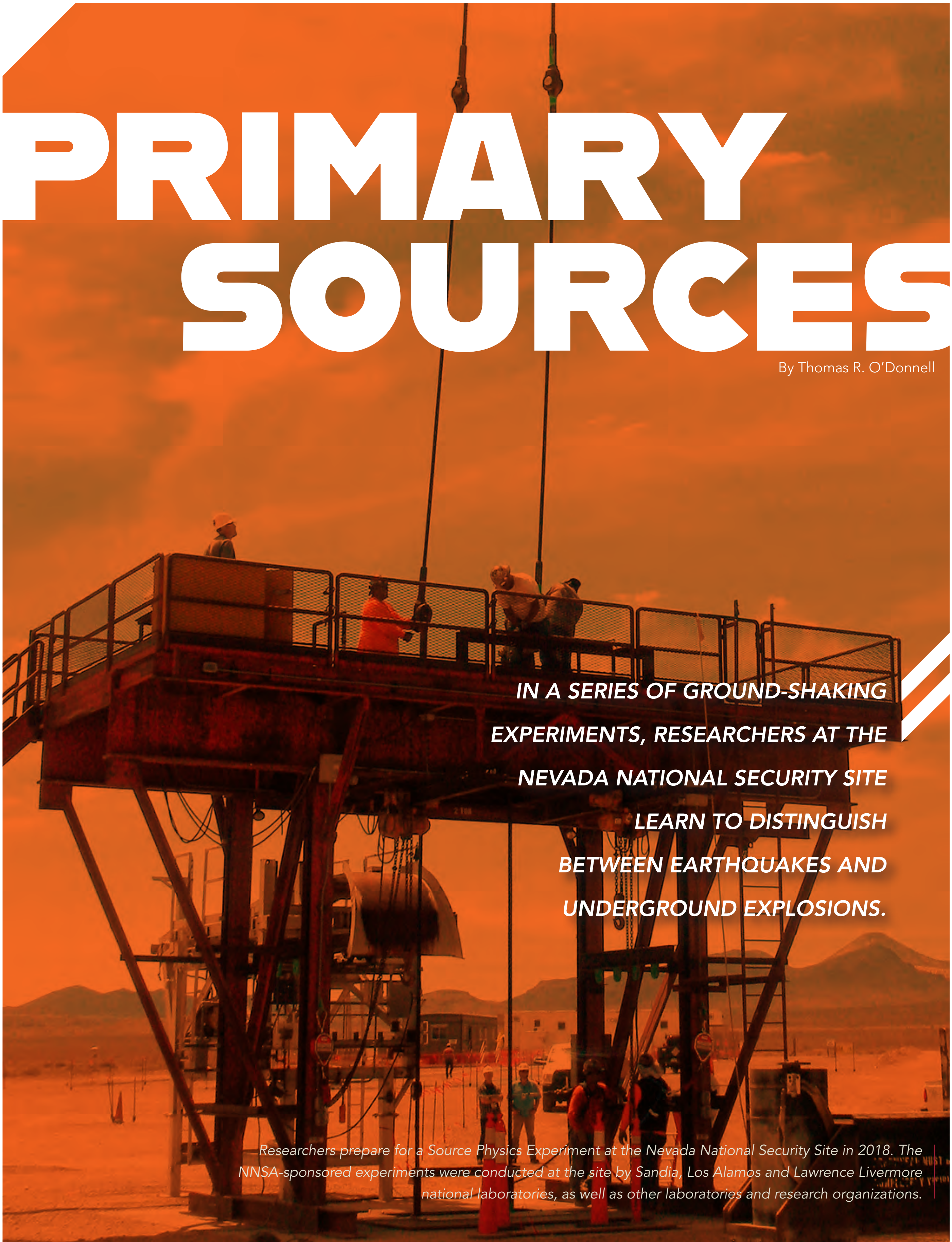
When Spriggs and his team examined these blasts, they found that EG&G miscalculated the yields in some of the Dominic detonations by 30 to 40 percent.

In an era of no atmospheric detonations – for nearly 60 years – DOE and DoD rely, at least partly, on information from past explosions to simulate future ones. Getting the right answers for today and tomorrow cannot be done with past data that are so inaccurate.

So Spriggs' project goes beyond historical preservation and scientific curiosity. The results of scanning and reanalyzing the films could play a crucial role in defense, he says. "If a 1megaton bomb is dropped in a specific place, what will be the fallout, where will the shockwave go and what will be the thermal output?" The data and calculations from his work could help provide answers.

First, Spriggs notes, the U.S. weapons community must see and assess what his team is doing and finding. "We're trying to get more scientific and accurate answers. We need to gain credibility in our new answers."

Spriggs calls the project a work in progress – a humble assessment after scanning and analyzing thousands of films and millions of frames. This work will open the eyes of anyone who makes time to watch these films, something people could be doing for another 60 years and beyond. There's much more to learn. "Every day," Spriggs says, "we end up going back and adding more data." SS



PRIMARY SOURCES

By Thomas R. O'Donnell

IN A SERIES OF GROUND-SHAKING EXPERIMENTS, RESEARCHERS AT THE NEVADA NATIONAL SECURITY SITE LEARN TO DISTINGUISH BETWEEN EARTHQUAKES AND UNDERGROUND EXPLOSIONS.

Researchers prepare for a Source Physics Experiment at the Nevada National Security Site in 2018. The NNSA-sponsored experiments were conducted at the site by Sandia, Los Alamos and Lawrence Livermore national laboratories, as well as other laboratories and research organizations.

Several times over the past nine years, Robert Abbott found himself in a trailer in the Nevada desert, his attention riveted on computer monitors displaying seismic instrument readouts.

He was about 1.5 kilometers from one of two holes, as much as a quarter-mile deep, on the Nevada National Security Site (NNSS), a Department of Energy (DOE) facility north of Las Vegas. Before Abbott and other scientists took their posts in the remote unit, technicians had sealed high explosives – the equivalent of up to 50 metric tons of dynamite – into the shaft.

"When it gets down to T minus nine, eight, seven, I'm quite nervous because I have to yell out immediately if I see anything that might compromise the data" – an earthquake or a human-caused event such as nearby mine blasting, says Abbott, a geophysicist and distinguished member of the technical staff at Sandia National Laboratories in New Mexico. Such an occurrence could ruin everything, obscuring readings the research team hoped to gather from dozens of instruments.

Several times, some problem – seismic interference or, more likely, a balky instrument – delayed the underground blasts, collectively known as the Source Physics Experiments (SPE). Nonetheless, all but one of the 10 happened later the same day.

The product: information scientists use to improve seismic models that identify and quantify underground nuclear weapons tests triggered in other countries. "We want to improve our nation's ability to monitor the world" for such blasts, helping detect nuclear proliferation, says Abbott, who oversaw Sandia's SPE participation. The data will improve the United States' ability to distinguish between testing and daily natural earthquakes, and to estimate an explosive's size and location.

SPE's other legacy: building a team to tackle a project unlike anything the United States has done in decades – at least since it stopped live nuclear testing in 1992. Multiple institutions and DOE facilities participated, including the NNSS and its management company, Mission Support and Test Services (MSTS); Lawrence Livermore, Los Alamos and Sandia national laboratories; the Defense Threat Reduction Agency; and the University of Nevada, Reno.

Although any underground explosion or earthquake will generate seismic waves, there are notable differences, especially in the kinds each produces. Primary waves compress material they travel through, similar to how sounds squeeze the air ahead of them. Underground rock and earth travel in the same direction as the wave.

In contrast, a shear wave results in particle motion transverse to the ray path. "If you rub your hands together, it generates more that kind of motion," Abbott says.

Instruments that record Earth's vibrations produce seismograms scientists analyze to distinguish explosions from earthquakes. Calculating the ratio of primary to shear waves, for example, is a proven way to identify each, says William Walter of Lawrence Livermore's geophysical monitoring program. But no one's sure exactly how it works, says Walter, who was chief scientist for many SPE shots, including all in phase 2.

Similarly, computer models used to understand seismic waves are mostly based on data from previous underground tests and less on the fundamental physics governing their propagation. SPE "was not just about the explosions, which get all the attention," Walter says. "The other half of the project was developing physics-based codes that can simulate what happens in an explosion and how the seismic signals are generated."

Another SPE science goal was understanding shear wave origins in underground blasts. "In theory, from the explosive shot, you should not generate shear waves," says Catherine Snelson, a program manager in the Earth and Environmental Science Geophysics Group at Los Alamos. Nonetheless, in "every explosion that has ever been recorded, we see shear waves," adds Snelson, who managed much of SPE phase 1 while at the NNSS and led the lab's role in the experiments after moving there.

SPE also has amassed data on small, low-yield weapons tests, which are more difficult to identify in seismic data than big

Sandia National Laboratories researchers (from left) Zack Cashion, Rob Abbott, Danny Bowman, Mark Timms and Austin Holland stand on an 8-foot diameter hole filled with gravel, sand, cement and explosives before a 2019 Source Physics Experiments test.

ones. Large blasts produce patterns resembling infrequent magnitude 6 earthquakes. Low-yield weapons generate waves similar to quakes of magnitude 3 or less. “There are millions of those quakes each year,” Abbott says.

Seismic waves from low-yield tests mostly travel through the Earth’s shallow crust rather than through the deeper mantle. That means they pass through a mixture of materials and terrain – rock and soil, solid mountain ranges and soft sediment basins – before reaching detectors. Those features scatter and reflect waves and alter their velocities, further obscuring a small explosion’s seismic signal.

SPE controlled many of these confounding factors. The 10 experiments used differently sized charges detonated at varying depths in the same two shafts and were detected by identically located sensors. That eliminated variables relating to seismic wave paths, instruments and geology near the explosion.

“Those all go away, and we’re left with the source effect” – how explosions appear in the resulting data, Abbott says. “We’re trying to eliminate as many variables as possible so we can get to what actually causes the differences” between underground tests and earthquakes.

Researchers compare SPE data with seismic information from Cold War-era nuclear tests at the NNSS, formerly called the Nevada Test Site, and in the former Soviet Union and China. For cost and safety reasons, however, most of those early explosions were detonated in a narrow band of depths. “There’s no reason to say that future proliferators will use that exact formula,” Abbott says, and there’s little data on small or shallow blasts. “SPE fills that hole a bit.”

To fill the hole, researchers first had to drill one for the initial phase in NNSS’s Climax Stock region. It was no ordinary shaft: 3 feet across and 300 feet down through granite. NNSS technicians hadn’t sunk something like that since the 1990s. “That was hard,” Snelson says. “We spent a lot of time drilling to get the hole where we needed it at the depth we needed it.”

Program managers Jesse Bonner and later Cleat Zeiler coordinated MSTS’s work with the laboratories and other project participants. The company had chief responsibility for preparing the test sites and for fielding an instrument array to gather explosion data. The team placed accelerometers to capture ground motion both in monitoring shafts and on the surface at varying points near the source. Farther away, technicians spread hundreds of geophones, microphone-like devices that measure earth vibrations, across more than a kilometer. (The geophones sometimes moved, thanks to unwanted help from four-legged research assistants.

Workers at the Nevada National Security Site lower the 25-foot-long Source Physics Experiments canister into the borehole to its center depth of 76.5 meters – about 250 feet – in preparation for its detonation in 2016. The explosives produced a blast equivalent to 5,000 kilograms of TNT.

THE THINGS THEY CARRIED OFF

Since the United States stopped live nuclear weapons testing in 1992, outdoor work has become rare – especially long-term projects like the Source Physics Experiments (SPE), says Lisa Garner, who managed its second phase for Nevada National Security Site contractor Mission Support and Test Services (MSTS).

"Being outdoors that long, dealing with the weather, the environment, the wildlife, was a challenge we didn't expect," Garner says. Especially the wildlife.

MSTS workers were in charge of placing diagnostic instruments to capture seismic waves and other data from SPE explosions in holes drilled on NNSS property. That included spreading hundreds of geophones, microphone-like devices that measure earth vibrations, across more than a kilometer.

But the geophones often moved. "Coyotes were voracious in picking up and carrying our diagnostics off," Garner says. The instruments, including cabling and battery packs, weighed several pounds, but the wily creatures lugged them 150 or 200 meters. "We spent a lot of money and time replacing cables and parts of instruments that had been dragged off and damaged."

The team tried a variety of commercial repellents and sprays to dissuade the thieves, but what worked best was ensuring the instruments were clean of any human skin oils. "So, basically a lot more glove work than we had intended," even in desert heat.

The team also dealt with ravens nesting in the rigging erected over the test holes. The birds are a protected species in Nevada, so technicians couldn't remove the nests and environmental officials supervised whenever the towers, nests and all, were moved.

Fortunately, relocating the rigging "did not appear to bother the ravens in the slightest," Garner says. "But that certainly was an unexpected challenge."

See sidebar, "The Things They Carried Off.") They placed sensitive seismometers at up to 50 kilometers' distance and accessed a University of Nevada, Reno, instrument network that stretches hundreds of kilometers.

Other detectors measured infrasound, blast-generated acoustic waves inaudible to humans. The researchers also trained high-speed video cameras on the experiment sites and photographed from unmanned aerial vehicles before and after the blasts to detect whether the earth permanently heaved or subsided.

For each experiment, crews sealed in the charges with layers of cement, gravel and sand to contain the blast and any resulting gases. NNSS technicians routinely performed such work until live testing stopped. When SPE came along, "most of the people who were previously involved were gone," says Lisa Garner, MSTS project manager for SPE's second phase. "They were retired or moved on to other positions." Workers had to learn skills and refurbish equipment needed to seal an explosive underground.

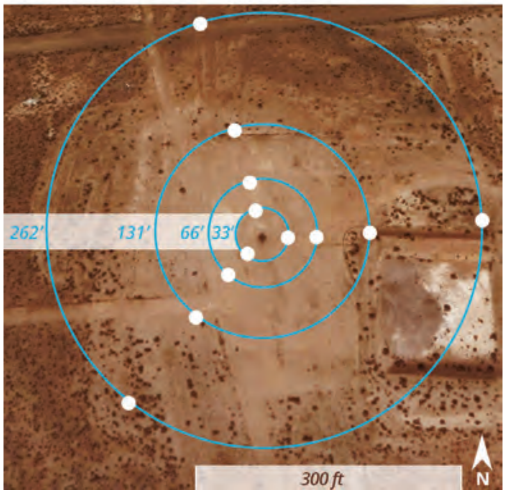
The first phase (designated SPE 1 through 6) ran from 2011 to 2016. Charges ranged in size from the TNT equivalent of 89 kilograms to more than 5 metric tons, exploded at depths from 31 meters to 87 meters. Shallow, low-yield experiments were designed to minimize spall – earth and rock that explosions throw into the air, possibly generating a secondary shock when they land – and produce data to compare with shear waves from deep, large blasts. The larger explosions were intended to produce seismic waves strong enough that regional instruments could detect them, allowing comparison with similar recordings of earthquakes and Cold War-era nuclear tests.

The second phase of four blasts, in 2018 and 2019, were in a never-used hole dating to 1983. Instead of granite, the shaft is in an NNSS region that's primarily comprised of alluvium, a soft material that eroded from the surrounding mountains and compacted over time.

"In a lot of ways, I would call alluvium the anti-granite," Walter says. "We really wanted a good contrast" between source regions to distinguish how a hard crystalline material and a porous, soft rock create shear waves and sustain damage.

Alluvium's properties meant phase 2 explosions – designated DAG, for dry alluvium geology – had to be about 10 times more powerful than those in phase 1. Because it's soft and riddled with air-filled pores that collapse, "the alluvium will soak up all that energy, attenuate it," and dampen seismic waves, Abbott says. With larger charges, the hole also had to be bigger – 8 feet in diameter – to keep the explosives

SPE Phase 2 Accelerometers



Depending on the experiment, up to 1,500 sensors were deployed to gather data for Source Physics Experiments (SPE) explosions. This aerial view shows accelerometer placement in 12 boreholes around the explosion source.

package compact and concentrate seismic energy in a way similar to that of a nuclear explosion.

DAG-1 and DAG-3 both generated blasts roughly equivalent to a metric ton of TNT, but the first was at about 385 meters deep while the second was at about 150 meters. DAG-2 was the biggest of all 10 tests: the equivalent of about 50 metric tons of TNT exploded about 300 meters below ground. DAG-4 detonated the equivalent of 10 metric tons just 52 meters deep.

The 10 tests, measured through hundreds of instruments, produced mounds of data – what experts have called the finest of its type in the world, Abbott says. SPE team members get first crack at analyzing the information and publishing papers before the raw data are posted on the internet.

Releasing the data lets other nations develop capability to identify underground tests, helping block nuclear proliferation. "It's an important topic for all of humanity, not just the nation," Abbott says. More importantly, "we make the data open-source so people can work on their aspect and advance the science" beyond DOE researchers' approaches.

The team's analyses have already suggested several conclusions and future research questions. First, SPE helped define weaknesses in existing models, most of which were based on extrapolations from experimental data. Those may fail if the explosion is shallow, deep or small – or a combination of those factors.

SPE led to a cycle of revising and validating simulations, Walter says. "We'd do predictions before each shot about what we thought would happen, we'd do the explosion, we'd look at the data and we'd revise the code." Through 10 shots, "we really improved the codes dramatically."

Second, the results showed how different geologies generate shear waves. In granite, the seismic rays encountered joints – cracks and small faults – leading to slips, similar to small earthquakes, that produced shear waves. The effect was found even near the explosion source, Abbott says.

Scientists didn't see the same outcome in data gathered near the DAG explosions. Discontinuity-related slips were infrequent and fewer shear waves resulted. They were more common in data recorded at a distance, possibly because seismic rays struck an interface between the granite and alluvium strata.

"The takeaway is the near-source data look very different from Phase 1 and Phase 2, based on these different mechanisms of shear regeneration," Abbott says. Sensors also detected less high-frequency seismic energy emerging from alluvium than from the Phase 1 tests. That suggested that alluvium more efficiently absorbed high-frequency waves through pore compression as compared to waves traveling through granite.

Much data analysis remains, however, including comparing results with those from decades-old tests in the same region. Such contrasts also are a major part of a proposed SPE phase 3, but with a difference.

"It would be an amazing experiment – absolutely amazing," Walter says. He and colleagues have wanted to conduct it since 1993, when instruments recorded shallow earthquakes on the NNSS reservation. The strongest tremor, at 3.7 magnitude, was centered at a depth of only 2 kilometers – "rare and unexplained to this day."

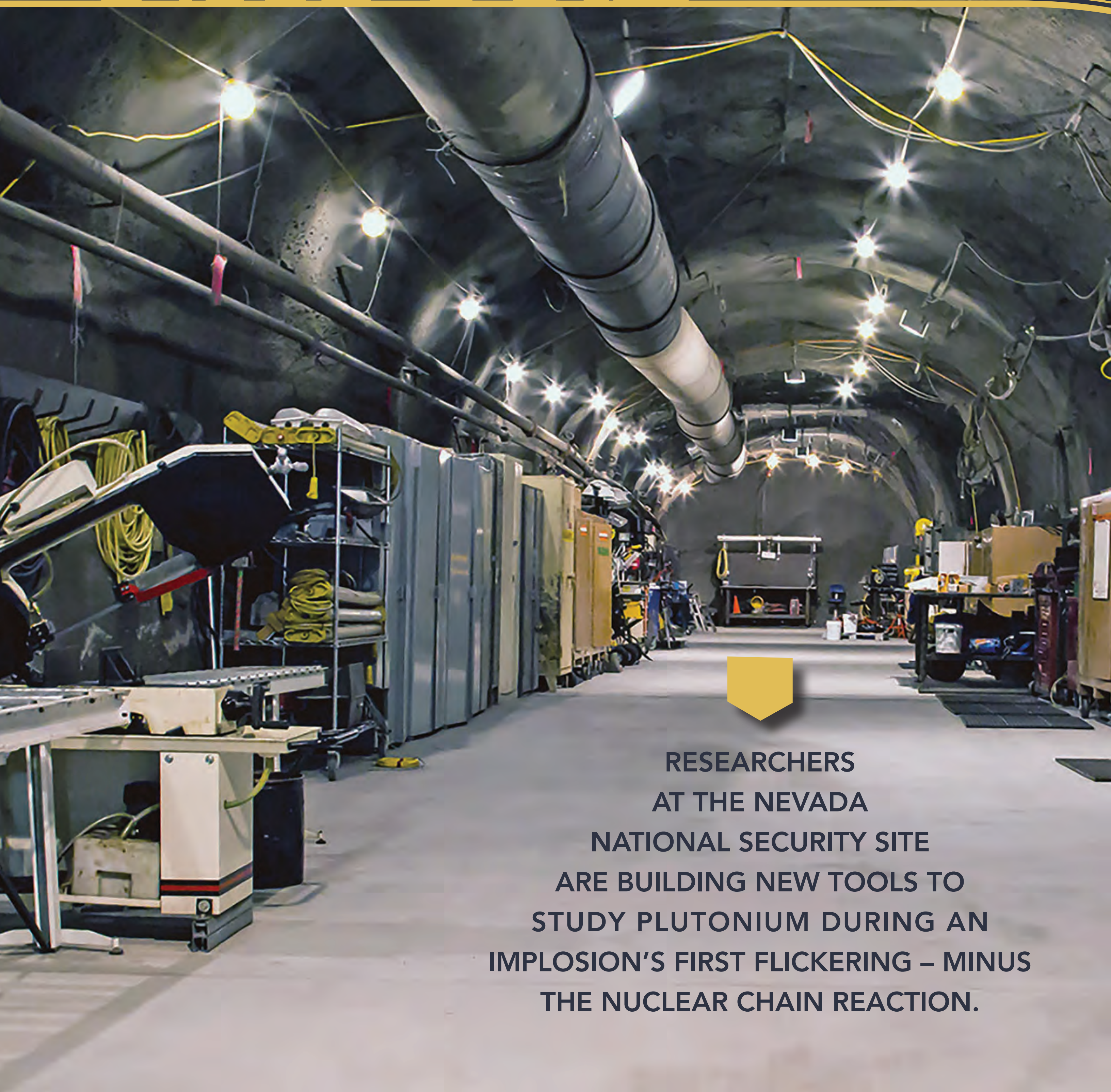
In phase 3, technicians would drill to the quake epicenter and plant explosives sized to generate similar energy. "It's a good case to really test a lot of our theory," Walter says, because it equalizes multiple variables. "You get right at the nitty-gritty difference between the two kinds of sources."

Lessons learned during SPE should make phase 3 easier, Garner says. "We showed we could conduct large chemical explosions in a pretty cost-effective manner" – and quickly, executing four DAG blasts in just under a year. "The emplacement and stemming capabilities that we revitalized" have made it simpler to prepare experiments.

For Los Alamos' Snelson, phase 3 is an opportunity to continue a rewarding multi-institution collaboration. "It's a harder problem, it's deeper drilling, it's in really hard geology, it's really challenging," she says, yet "hopefully we'll be able to bring the band back together again. It would be fun." SS

SUBCRITICAL NATURE

BY SARAH WEBB



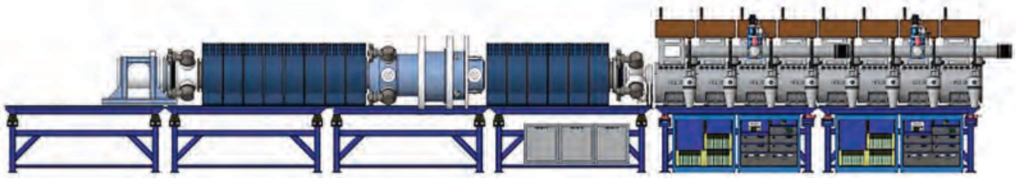
RESEARCHERS AT THE NEVADA NATIONAL SECURITY SITE ARE BUILDING NEW TOOLS TO STUDY PLUTONIUM DURING AN IMPLOSION'S FIRST FLICKERING – MINUS THE NUCLEAR CHAIN REACTION.

A tunnel at the Nevada National Security Site's U1a facility.

Nearly a thousand feet below the desert, tunnels support experimental work to maintain the U.S. nuclear weapons stockpile. Here, in the Enhanced Capabilities for Subcritical Experiments facility now under construction, researchers are building two instruments – a high-energy X-ray probe and a sensitive and fast neutron reactivity diagnostic – that will work in concert at the Nevada National Security Site's (NNSS) U1a complex to study plutonium in the fraction of a second after implosion.

These instruments, Scorpius and the neutron-diagnosed subcritical experiments (NDSE), will apply emerging technologies to questions about aging plutonium. "We don't manufacture materials necessarily in the same way that we had in the past," says Los Alamos National Laboratory's Dave Funk. "Or we may want to investigate new manufacturing opportunities to reduce cost and for the overall upkeep of the stockpile."

Since underground nuclear weapons testing ended more than 25 years ago, scientists at the Department of Energy National Nuclear Security Administration (DOE NNSA) facilities have relied on stockpile stewardship – a combination of sophisticated computer models and experiments – to certify the safety, security and reliability of U.S. nuclear weapons. To ensure that models reflect how weapons materials behave, researchers compare them with experimental data. Some of that information comes from historical underground tests conducted until 1992. But past data can't address current and future questions about radioactive decay's effects on aging weapons or how replacing or refurbishing parts might affect weapon performance. Researchers need new real-life physics data to validate computational predictions.



Scorpius is the high-energy X-ray component of the Enhanced Capabilities for Subcritical Experiments facility currently under construction at the Nevada National Security Site. The facility will produce X-rays up to 20 MeV and will be able to take at least four snapshots during the first few microseconds of a test device's implosion.

To study these materials, scientists turn to hydrodynamic experiments that use high explosives or high-energy pulses to implode a test device, generating extreme pressures and temperatures for a millionth of a second that cause the core materials to flow like liquids. Sophisticated rapid detectors then measure how these materials change and respond over that fleeting span.

Some hydrodynamic tests use surrogate metals, non-fissile elements with densities similar to plutonium's. Such tests can be conducted at NNSA's Contained Firing Facility at Lawrence Livermore National Laboratory and at Los Alamos' Dual-Axis Radiographic Hydrodynamic Test (DARHT) facility, on which Scorpius is partly modeled. Based on DARHT experiments, researchers will refine theoretical models, Funk says, "to more accurately predict the electron beam dynamics on Scorpius, which will lead to improved performance." (See sidebar, "From DARHT to Scorpius.")

But plutonium is central to how weapons function, and researchers need data about it to constrain their models. Besides its radioactivity and toxicity, plutonium's chemical and physical properties are unique (see sidebar, "The Plutonium Puzzle"). "It's not obvious that our understanding of surrogate metals would actually translate to the real behavior of plutonium," Funk says, so NNSA researchers also conduct hydrodynamic tests with the real thing to learn more about its strength and equation of state – mathematics that describe how temperature, pressure and volume interact. These experiments are subcritical, meaning the implosions don't achieve the neutron density to sustain a nuclear chain reaction.

To ensure they stay that way, neutron diagnostics carefully monitor these experiments. Like other types of nuclear fission, plutonium nuclei split into (usually two) smaller nuclei and neutrons while emitting gamma rays and energy. But unlike nuclear reactions in power plants or weapons, these tests cannot reach the critical density necessary to sustain a nuclear chain reaction. As a result, they fizzle out quickly, in a fraction of a second.

Researchers have conducted around 30 subcritical experiments at the Nevada site since 1993. Some have measured particular plutonium properties, producing data that allowed researchers

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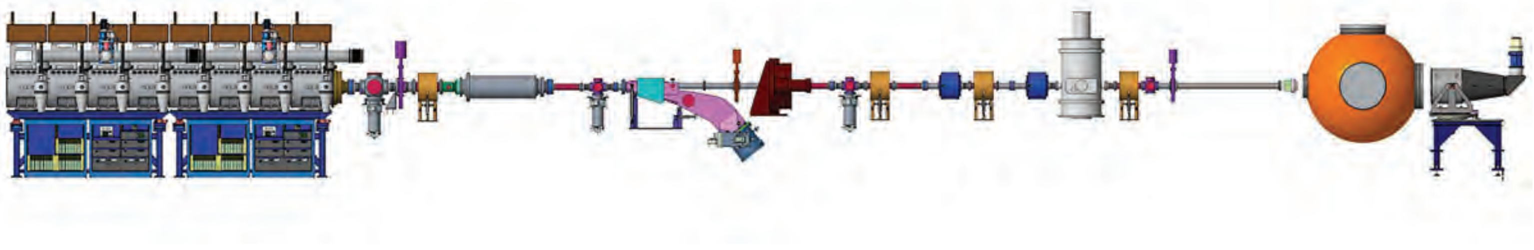
THE PLUTONIUM PUZZLE

Discovered 80 years ago, plutonium is almost completely manmade, and its fission characteristics sit at the core of nuclear-weapons technology. Experiments with plutonium are daunting – the metal is radioactive, reactive and toxic, and it's subject to stringent criticality and security constraints.

Beyond all that, plutonium remains mysterious. For one thing, whereas researchers can make decent chemical and physical predictions of most elements by studying neighbors on the periodic table, plutonium is far less tractable. It isn't even as magnetic as the periodic table predicts.

And small changes in temperature and pressure alter the number of electrons that each atom shares with others. Even at ambient pressure, heated solid plutonium can exist in up to seven different atomic arrangements, or allotropes. And unlike other metals, plutonium becomes denser as it melts.



to set critical parameters in NNSA computational models, says Mike Furlanetto, who leads the subcritical experiment program at Los Alamos. Others have tested multiple physical phenomena to ensure that NNSA models can predict more complex interactions.

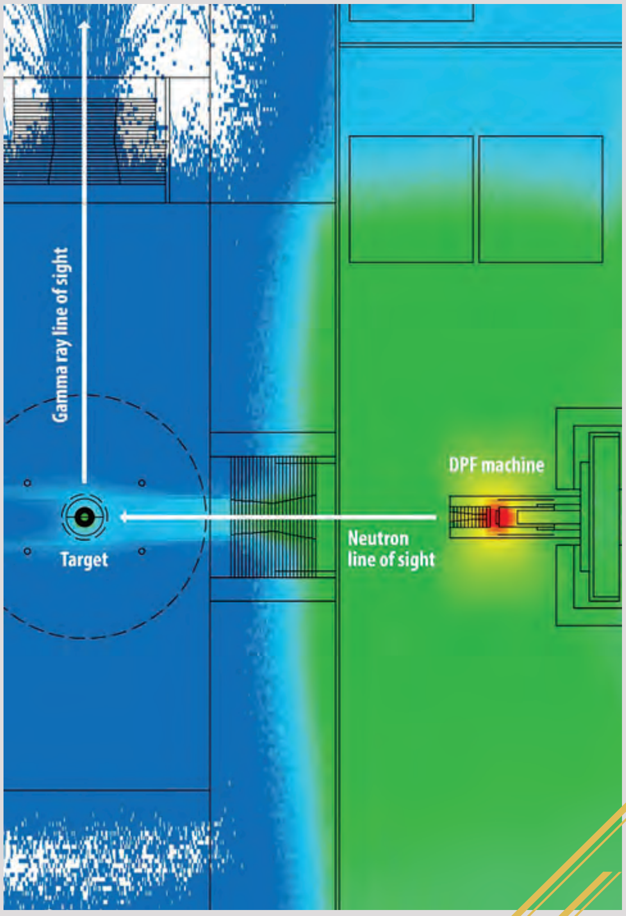
"Technically," Furlanetto says, "because the plutonium in a nuclear weapon is subject to an extremely wide range of pressure and temperature states, it is difficult to field experiments that match both the required states and provide enough time and access to make precise experimental measurements."

In the absence of total weapons testing, researchers can't observe some of the relevant states, he adds. "Subcritical experiments are the closest match to the relevant conditions."

Previous subcritical experiments used an assortment of precise techniques to observe plutonium on these extremely short time scales. Electrical and optical ranging allow researchers to measure the position of plutonium samples. With advanced velocimetry, a laser technique, researchers can measure the speed and acceleration of plutonium surfaces. Scientists also use other diagnostics to measure the exact positions of plutonium samples and their ejecta, small particles released from the metal's surface when a shock wave hits.

Radiography experiments are a central tool in subcritical research. Low- and medium-energy tests already have provided data about plutonium's density and distributions. In these experiments, X-rays probe plutonium samples. Then scintillators convert the X-ray signals into light, allowing the detector to take snapshots of plutonium. Cygnus, the current instrument at the NNSS's U1a facility, produces X-rays with a maximum energy of 2.2 million electron volts (MeV) and can take two images per experiment. At that energy, approximately 100 times greater than a dental X-ray, the radiation can penetrate thin slices of plutonium but can't probe the larger sizes and shapes that more closely resemble weapons materials, Funk says. "You need much higher energy."

For those experiments, researchers need a radiography system of at least 20 MeV. That's where Scorpius comes in. Named for the brightest visible X-ray source outside our solar system, this instrument will focus and boost the energy of electron pulses, converting them to up to 20 MeV X-rays. The detectors will be able to take at least four snapshots during the first few microseconds of a test device's implosion. Los Alamos scientists are leading the Scorpius work with components and support from the other NNSA labs.



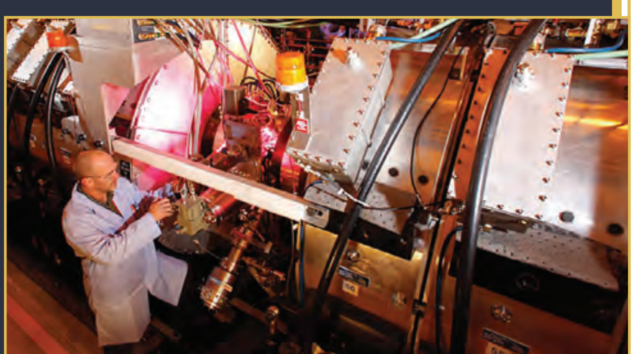
A computer simulation showing the setup of a neutron-diagnosed subcritical experiment. Trillions of neutrons travel, one at a time, from the dense plasma focus (DPF) machine to the target. Gamma rays (and neutrons) then leave the target in all directions at once, and some travel toward gamma-ray detectors.

FROM DARHT TO SCORPIUS

The Dual-Axis Radiographic Hydrodynamic Test (DARHT) facility at Los Alamos is among the largest X-ray installations in the world, accelerating electrons at dizzying speeds to produce X-rays with energies of 20 million electron volts. DARHT places a weapon-like pit at the cross point of two accelerators arranged at right angles from each other. The facility can grab up to four rapid-fire snapshots in millionths of a second in one direction and a single image in the other, allowing researchers to infer three-dimensional effects.

Scorpius's X-rays will match DARHT's energy, but the whole system – including an accelerator more than 300 feet long – will be contained in a single 420-foot-long tunnel being mined at U1a. Based on DARHT experiments, researchers will refine theoretical models. They're also hoping to improve experiments' signal-to-noise ratio by altering how instruments convert X-rays to visible light and by tweaking the detection system.

Unlike DARHT, where the short pulses are formed by chopping up a single 1,500-nanosecond pulse, Scorpius will generate multiple pulses with modern solid-state pulsed-power drivers. This feature will allow researchers to tailor both the pulse widths and numbers for particular hydrodynamic tests.



Scorpius is modeled in part on the Dual-Axis Radiographic Hydrodynamic Test Facility (DARHT) at Los Alamos National Laboratory, one of the largest X-ray installations in the world.

Alongside Scorpius, researchers from Los Alamos, Livermore and NNSS are building NDSE to detect fission-emitted gamma rays, enabling measurements of the fission decay rate in a subcritical device. Such measurements are possible because researchers have developed bright initiators of fission and can distinguish the neutron signal from background sources.

This time-dependent reactivity depends on several important quantities, says Russ Olson, a physicist with Los Alamos' Neutron Science and Technology Division. These include the plutonium's density, its fission cross-section and how surrounding materials affect neutron transport throughout the entire assembly. Other experiments and computational techniques can independently determine those last two quantities, he says. "NDSE is really providing an indirect measure of the plutonium density at a particular time during the implosion."

A factor that has limited measuring subcritical reactivity: statistical noise. "A sufficient number of fission events must occur to rise above the background levels in the U1a environment," Olson says. NDSE are now possible because researchers can produce an intense, short-pulse external neutron source that helps initiate many initial fission events and thereby reduce the measurements' uncertainty. In addition, pulses must be brief enough to match experiments' infinitesimal time scales.

The NDSE team had planned to use only a dedicated neutron source to generate those initial fission events. But simulations and data suggested Scorpius would produce so many neutrons and gamma rays it would dwarf the NDSE signal of interest. The team realized that it could get around the noise problem by using the high-dose Scorpius X-rays to initiate the neutron reactivity measurements. At energies above about 10 MeV, X-rays can cleave plutonium nuclei directly, without generating a neutron first.

So researchers are designing the two instruments to work together. Scorpius' accelerator can initiate fissions for the NDSE as it simultaneously generates X-ray pulses for radiography. And they're altering the detector design so it can measure the NDSE fission gamma rays while it's shielded from Scorpius' copious particle and radiation scattering.

The Scorpius and NDSE teams plan to begin experiments in 2025, starting with life-extension program research for the W80-4 nuclear warhead, designed in 1976. The instruments are expected to support stockpile stewardship experiments for at least the next 30 years. SS

The Stresses and Rewards of Subcritical Science

Stephen Sterbenz is senior technical advisor for stockpile experimentation and operations at the Nevada National Security Site (NNSS). He moved to NNSS in 2016 after more than 25 years at Los Alamos National Laboratory where, among other roles, he led the Primary Design Physics Group. Sterbenz spoke with Stewardship Science's Sarah Webb. His remarks were edited for space.

How did you become interested in the science behind nuclear weapons?

While I was a postdoc I was stationed at what is today known as the Los Alamos Neutron Science Center (LANSCE), and I became intrigued with the science, technology and broader implications of nuclear weapons. I was inspired by the history of Los Alamos, and underground nuclear testing was still going on at the time. I developed a technical fascination: What are we still doing here all these decades after the Manhattan Project? What do we still need to do?

In early 1990, I joined Los Alamos as a staff scientist in the weapons program. I worked for a few years as a prompt diagnostics physicist on underground nuclear tests before the moratorium began in October 1992.

What are today's key technical challenges in stewardship science?

Experiments involving plutonium are difficult wherever and whenever you do them. The NNSS is a unique national resource: a venue where we can combine high explosives with quantities of plutonium in dynamic tests.

Experiments involving plutonium are difficult wherever and whenever you do them.

Subcritical experiments are carried out more than 900 feet underground at a facility we call U1a and adhere to our nation's policies under the nuclear test moratorium, never achieving a runaway chain reaction. They focus on the material properties of plutonium in various configurations that are relevant to nuclear weapons science and are considered by our colleagues at the NNSA laboratories to be vital to the stewardship mission. A centerpiece of these experiments has been the Cygnus dual-axis X-ray radiography facility in U1a that was put in place in 2005 as part of the amazing collaboration we have had with Los Alamos National Laboratory on subcritical tests. A next-generation X-ray radiographic capability called Scorpius is now under development, along with a new diagnostic capability called neutron-diagnosed subcritical experiments, or NDSE. Together with the national laboratories, we will bring NDSE and Scorpius on line as critical capabilities for stockpile assessment by the middle of this decade. (See "Subcritical Nature," this issue, page 18.)

Another important initiative at the NNSS is carrying out high-pressure experiments on plutonium and other materials at the Joint Actinide Shock Physics Experimental Research (JASPER) facility, a collaboration between Lawrence Livermore National Laboratory and NNSS. JASPER features a two-stage gas gun and extensive experimental diagnostics and is used to conduct exquisitely precise measurements on plutonium and other materials of interest.

What role do the SSGF and LRGF play in training new scientists to work on these technical challenges?

When I first worked on the SSGF selection committee while at Los Alamos, I was impressed with the extremely gifted students in the program, many of whom became or are becoming high-achieving research scientists at the national laboratories. The practicum experience at one of the three national security labs – Livermore, Los Alamos and Sandia – has been a key element of that program. One unique feature of the LRGF is that it includes the opportunity for a research experience at NNSS.

What unique research opportunities are available with NNSS?

Today's subcritical experiments are a bit like a space shot. Diagnostic equipment that you spend months, or even years, working on is often expended within microseconds. It can be a stressful experience, but it's usually a very rewarding one.

NNSS staff partner with other laboratories in developing new techniques used to interrogate dynamic properties of materials including plutonium. We are often the ones responsible for bringing well-engineered diagnostics to the field, and our engineers, physicists and mathematicians help analyze dynamic experiment data once they are taken.

Research work at NNSS isn't confined to the Nevada site. We have support facilities at all three national security labs and an experimental facility in Santa Barbara, California. Residencies could involve work at any, or even all, of these sites. NNSS supports experimental work at venues including at Los Alamos's DARHT and LANSCE facilities, Sandia's Z-machine and Livermore's Site 300.

Scorpius and NDSE will allow the next generation of experimentalists to experience real-world challenges and expand their scientific horizons and will foster national and international collaborations.

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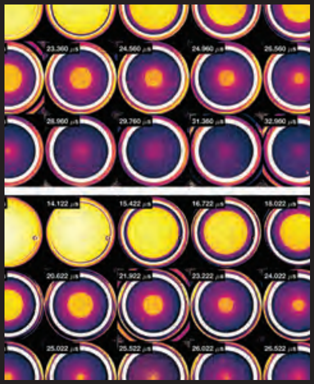
KEY
(academic advisor); national laboratory practicum location:
LANL = Los Alamos
LLNL = Lawrence Livermore
SNL = Sandia National Laboratories
TBD = to be determined



COMPRESSIONS
EXPRESSED

A composite radiograph from two compaction experiments at Los Alamos National Laboratory's PHELIX facility. Read more in "Fellows on Location," starting on page 2.

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